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14. ABSTRACT

Highly impulsive movements are some of the most extreme and mechanically challenging examples of animal movement, employing high forces and powers to achieve spectacular accelerations and velocities of all or part of the animal's body. The strikes of snakes are one of the most remarkable impulsive movements in animals combining the characteristics and challenges of both feeding and locomotive impulsive motions. Snakes must rapidly accelerate a large fraction of their body mass using an extremely complex musculo-skeletal system in order

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Report Title

Final Report: Principles Governing the Mechanics and Control of Snake Strikes

ABSTRACT

Highly impulsive movements are some of the most extreme and mechanically challenging examples of animal movement, employing high forces and powers to achieve spectacular accelerations and velocities of all or part of the animal's body. The strikes of snakes are one of the most remarkable impulsive movements in animals combining the characteristics and challenges of both feeding and locomotive impulsive motions. Snakes must rapidly accelerate a large fraction of their body mass using an extremely complex musculo-skeletal system in order to accurately strike a small, potentially evasive target with an impact sufficient for prey capture but without damaging their lightly-built skull. Although the performance, ecology, and kinematics of strikes have been examined previously, the underlying mechanics producing these motions have never been examined. We propose to investigate the mechanics of snake striking, within and across the diverse species available to us through our collaboration with Zoo Atlanta. In this exploratory project we will monitor kinematics, ground reaction forces and strike forces in snakes to gain insight into common principles governing mechanics and control of strikes. We expect that discovery of important features of such strikes will be useful to inform physics of impulsive locomotor control.

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Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

see attached

Technology Transfer

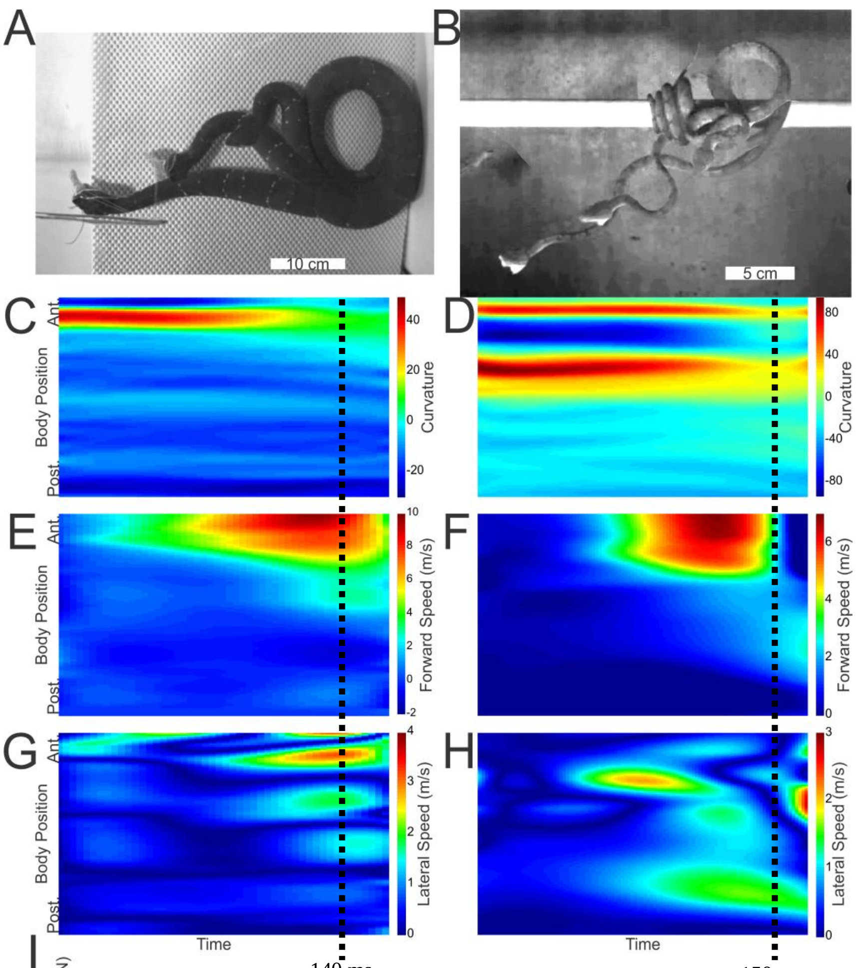
Report on STIR "Principles governing the mechanics and control of snake strikes"

Daniel I. Goldman, School of Physics, Georgia Institute of Technology

During this project, we began a study of the mechanics of snake striking, which is currently ongoing. The project has been divided into two components: biological and robotic. This funding has also been useful to allow a biology postdoc (Dr. Henry Astley) to focus his skillset in collecting and analyzing data on an organism, as well as to develop a new skillset in physical and mathematical modeling of behaviors. It has also enabled him to interact with Prof. Howie Choset's group at CMU to aid his entry into "robophysics" and physical modeling.

Biological snake striking

We have obtained high speed video recordings for several species of striking snakes, including three of the



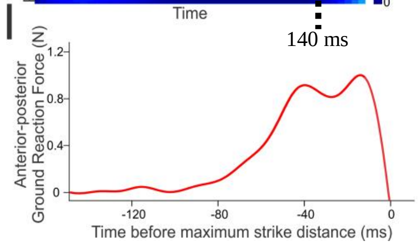


Figure 1 – A) Cantil (*A. bilineatus*) striking sequence. B) Amazon tree boa (*C. hortulanus*) striking sequence. C) Body curvature during a cantil strike along the snake (vertical axis) over time Body curvature during an Amazon tree boa strike. E) Forward speed of body segments during a cantil strike. F) Forward speed of body segments during an Amazon tree boa strike. G) Lateral speed of body segments during a cantil strike. H) Lateral speed of body segments during an Amazon tree boa strike. I) Forward ground reaction force during a cantil strike. Dashed lines in C-H indicate the time of

most diverse families of snakes: vipers, colubrids, and boids. We also acquired ground reaction force recordings from the viper, the first force recordings of any snake strike.

In Figure 1, you can see two exemplar strikes from very different species. The left panels show a feeding/envenomation strike of a cantil (*Agkistrodon bilineatus*), a heavy-bodied terrestrial viper, while the right panels show a defensive strike of an Amazon tree boa (*Corallus hortulanus*), a slender-bodied arboreal boa. Both snakes reach extremely high speeds (>7 m/s) (Fig. 1CD) in less than 150 ms (versus a human eye blink of ~300 ms). This impressive and similar performance is achieved by very different mechanisms; the viper primarily drives its strike by straightening two relatively shallow bends in the body, while the tree boa uses three much tighter bends. Consequently, in spite of similar size (90 cm vs 75 cm), the tree boa has a much longer reach (32 cm vs. 22 cm), at the cost of a slightly lower peak speed and longer duration. However, because viper's posture relies on a single large bend, it has higher velocities perpendicular to the strike (Fig. 1 GH) and thus more wasted energy.

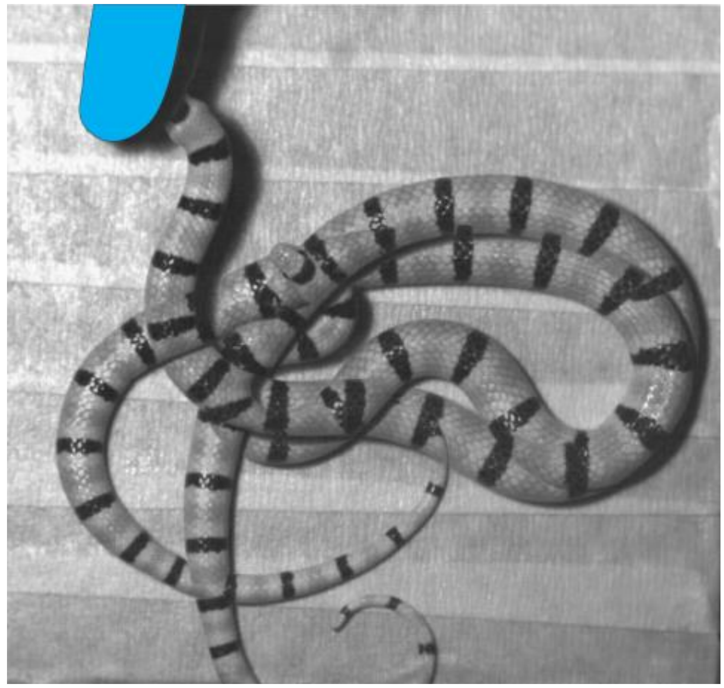


Figure 2 – Defensive strike of a Western shovelnose (*Chionactis occipitalis*) at a 3D-printed target. Total strike duration was 120 ms.

Another key difference is anchoring, and the consequences for the strike. A snake which lays flat on the ground or other surface may only exert as much forward thrust as the animal's body weight multiplied by the coefficient of friction, else it may slip backwards (Fig. 2). But when gripping an arboreal perch, the force of the strike is limited only by the strength of the snake. In spite of this, the terrestrial cantil achieved the highest speed, pushing back with 40% of its body weight and negligible slip.

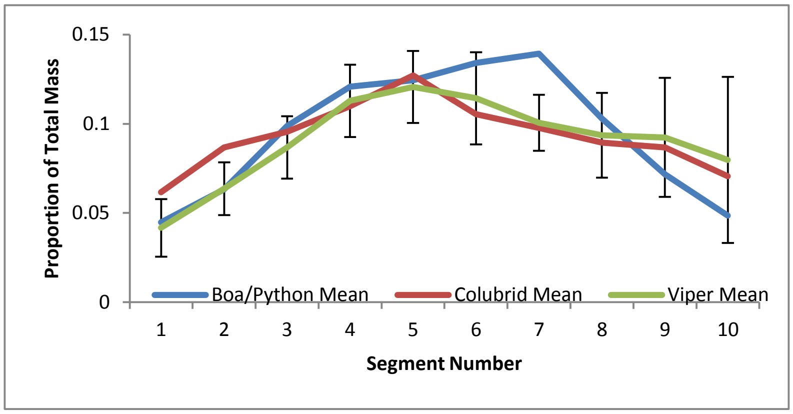


Figure 3 – Proportion of body mass in each of 10 equal-length segments comprising the snake's body, assessed from dissection specimens. Most species have comparatively light-weight anterior bodies, possibly to aid in striking.

We have additionally collected measurements of segmental masses, muscle masses, and morphology from a wide variety of snake species via dissection of museum specimens. This will allow us to more thoroughly link kinematics to forces, explain differences between species and behaviors, and develop a parameter space for exploration with our robotic model (see below).

Analysis of the collected data is ongoing, along with the development of an automatic tracking algorithm to allow more rapid processing, which will expedite further data acquisition across a broader range of species once Zoo Atlanta is again open for research collaboration; their renovation and expansion of herpetological facility has limited our collaborative activities, although we expect to resume experiments by mid July 2015.

Robotic experiments

During the period of this grant, we began development of a “robophysical" multipurpose robotic snake, which will eventually be capable of both effective locomotion and adopting a variety of striking behaviors. This robot is not intended for use in the field, but for use in discovering principles in the laboratory which can then be implemented on a hardneded limbless robot. Aside from the servomotors and wires, these robots consist entirely of 3D-printed parts, allowing rapid reconfiguration for various experimental purposes. The central backbone is covered in protective shells, and, thanks to 3D printing, the length, mass and rotational inertia of each segment can be independently modulated to explore the effects on behavior. Masses can be added at different positions to exclusively vary rotational inertia without affecting other factors, thereby simulating differing snake morphology. Head and tail segments will be able to be rapidly swapped between locomotion and striking configurations, the latter consisting of a grasping head and statically anchored, force-sensitive tail. The first prototype served as a means for the associated post-doc to learn robotics and develop the general plan for these robotic snakes. Unfortunately, the limitations of 3D printed material strength and servo mass-specific power make it hard for it to support itself, necessitating the construction of a more advanced,

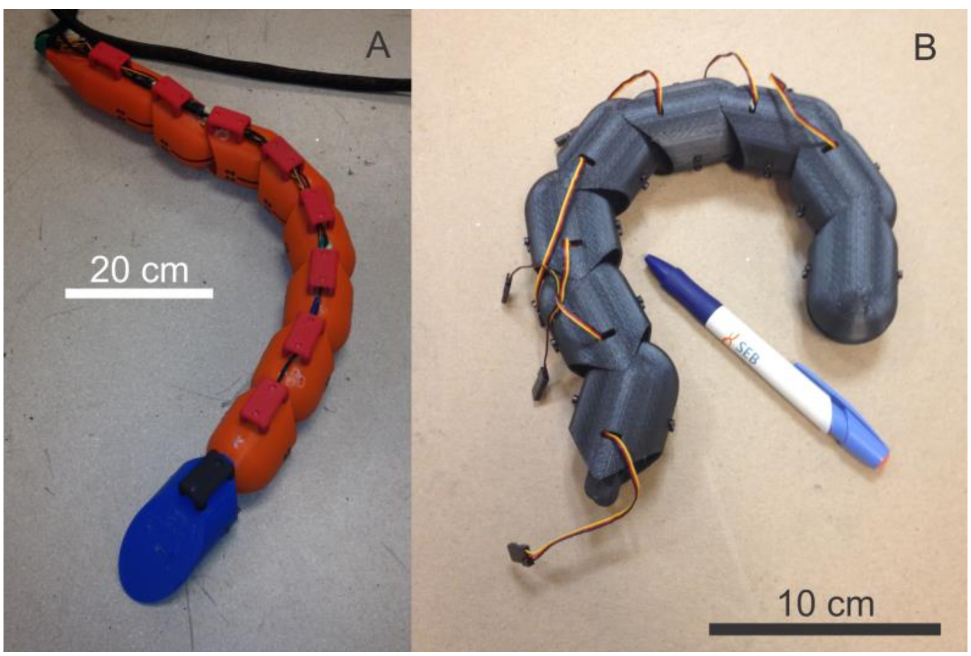


Figure 4 – 3D printed, servomotor-driven robotic snakes. A) Version 1, 8 segments, total length 82 cm, mass 1.3 kg. B) Version 2, incomplete (7 segments operational), estimated total length for 16 segments 76 cm, mass 0.29 kg

lightweight robot, which will be less than 1/4th of the mass but with twice as many as degrees of freedom. Once completed, we will be able to thoroughly explore parameter space related to striking, complementing biological studies.